BIL-7

N-93075

ATOMS AND SPACE

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(Paper Presented at the 1959 Annual Conference of the Atomic Industrial Forum, Washington, D. C., November 3, 1959)

Introduction

The stated subject of this paper is so broad that it might include everything from the study of the infinitely small recesses of the atom to the vast infinity of galactic space. We will therefore begin by limiting the scope of the subject to a discussion of three questions: --- (1) What are the potentialities of the use of nuclear energy in the exploration of space? --- (2) What uses of nuclear energy in space exploration are expected in the next decade? --- (3) What is likely to be the impact of space exploration on the development of other applications of nuclear energy?

We will discuss these questions in relation to the space activities of the United States as set forth in the National Aeronautics and Space Act of 1958 and in the programs of the National Aeronautics and Space Administration, the agency established by Congress to carry out the policy established in that Act that activities in space should be devoted to peaceful purposes for the benefit of all mankind. Such activities include at present the exploration of space to gain greater knowledge and understanding of the earth and its atmosphere, the moon, planets, and the universe; the application of available knowledge to develop capabilities for other activities in space for the benefit of mankind; and the beginning of the exploration of space by man himself.

A program of this magnitude must be undergirded by a broad program of research and development in many fields of technology and by vigorous development of advanced technology at the frontiers of knowledge. The most visible aspects of the program are, however,

the actual flight missions of space vehicles. In the current program these missions include those connected with scientific measurements in sounding rockets and earth satellites, lunar and interplanetary missions, meteorological satellites, passive communications satellites, and missions leading to manned satellite flight. As we look down the road we see more advanced missions, including hard and soft landings on the moon and planets, orbiting astronomical laboratories, circumlunar flights by man, landing of man on the moon and return, etc.

Mission Requirements

Whatever the mission, we find that propulsion systems are the key to possible accomplishment, whatever the specific objectives. We find now to our regret that we do not have propulsion systems required for the payloads for many of the missions we need to undertake. In fact we are unable to carry out many missions because we do not have the thrust required to carry available precise guidance systems in the final stage and hence can not perform those missions requiring precise guidance.

Our present capability has been further limited by the unavailability of upper stage rockets of the proper sizes to match the capabilities of the intercontinental missile boosters available for use as the first stage of a space vehicle. We have been compelled to use available rockets from the Vanguard satellite or other missile programs.

Energetic steps are being taken to develop as quickly as possible the required propulsion and vehicle capabilities, including optimized stages for the Atlas and Thor and new rocket engines with a thrust exceeding one million pounds. Although these early developments are based on chemical fuels, attention has been given to nuclear fuel. Before discussing the use of nuclear energy, it is well to review space mission requirements expressed in general terms.

From the standpoint of propulsion requirements any proposed space mission may be defined in terms of the velocity increment to be given to the final stage of the vehicle. Thus the mission of launching a probe from the earth to escape the earth's gravitational field as a one-way interplanetary probe requires a velocity increment from the velocity due to the earth's rotation to escape velocity, i.e. of about seven miles per second. If started from an earth orbit, the increment required is about two miles per second. An increment of about

100 miles per second is required to explore the entire solar system. In all missions the effects of gravitational forces and air resistance can be incorporated as an equivalent addition to the velocity finally acquired by the last stage to give the so-called "characteristic velocity" of the mission. The characteristic velocity for a single stage ground launched vehicle from Earth to Mars and return is about 25 miles per second.

Turning to a rocket propulsion system, the characteristic velocity added by a single stage depends primarily on the specific impulse of the propellant and the ratio of final weight to initial weight. The characteristic velocity is directly proportional to the specific impulse of the propellant. The weight ratio dependence is more complicated. In addition a change of propellant usually changes the weight ratio as well as the specific impulse especially if the engine type involves a change in the ratio of engine weight to gross weight. Hence accurate comparisons require preliminary design of vehicles incorporating each system.

Applications of Nuclear Energy

Since nuclear fission produces about ten million times as much energy per pound as the best chemical rocket propellants, there are obvious attractions in the use of nuclear fuel. Rocket propulsion, however, requires not only a source of energy but a means of utilizing the energy to overcome gravitational and air forces and accelerate the vehicle to a high speed. This requires a continuous supply of propellant to be ejected from the vehicle to give thrust.

Nuclear fission has been used to produce energy in the form of detonation of nuclear weapons and in the form of heat as in applications to the generation of power in ships and on land. In 1947 Ulam of the Los Alamos Laboratory proposed to produce thrust for a large space vehicle by using the thrust of a series of small nuclear explosions in rapid sequence, an idea that is undergoing further study at Los Alamos under support of the Atomic Energy Commission and at General Atomics under a contract from the Advanced Research Projects Agency of the Department of Defense.

The more conventional application of nuclear fission is to the nuclear rocket in which a reactor is used to add heat to a propellant which expands through a rocket nozzle to give the propulsive jet. Project Rover, a cooperative program between the AEC and NASA is intended to explore and demonstrate the feasibility of developing such a system.

In addition to applications of nuclear energy to the main propulsion system, there is much interest in nuclear energy as the source of auxiliary power in satellites and space probes. Communications equipment, auxiliary systems for attitude control, modification of orbits, and sensing devices for physical measurements present continuing needs for power for as long a life as practicable. Many of the systems use electrical power and hence energy conversion devices are essential parts of an auxiliary power system for satellites.

There is much speculation about the development of nuclear fusion as a source of energy for space applications, but until this method has been demonstrated for ground application, no serious work can be undertaken on space applications. It may be worth pointing out that for small power levels, solar power, which arises from nuclear fusion within the sun, is and will find useful application in satellites and space probes.

Nuclear Rockets

The potential performance of nuclear rockets has been reviewed in numerous recent publications, for example, "Potentialities and Problems of Nuclear Rocket Propulsion," by T. P. Cotter of the Los Alamos Laboratory in the February 1959 issue of Aero/Space Engineering, and four papers in the October 1959 issue of Astronautics by Frank E. Rom of NASA, Jerry Grey of Princeton, Franklin P. Durham of Los Alamos, and Robert W. Bussard of Los Alamos.

The specific impulse of any rocket, including the nuclear rocket, is approximately proportional to the square root of the ratio of the absolute temperature of the propellant before expansion to the bulk molecular weight of the propellant. Thus the propellant should have the lowest possible molecular weight, leading to hydrogen as

the most desirable propellant. The temperature should be as high as possible and is usually determined by the materials used. This requirement leads to the necessity for engineering compromises.

Rom points out that potentially uranium fission can produce specific impulses of the order of hundreds of thousands (compared to about 400 for the best high energy chemical fuels) but at operating temperatures of hundreds of billions of degrees Fahrenheit. Obviously a compromise must be made.

In a solid-fuel-element reactor such as the Kiwi-A reactor recently tested in Project Rover, the temperature of the propellant is limited by the melting points of the solid materials containing the fissioning material. The most refractory materials, not yet usable in practice, are the carbides of hafnium and tantalum which melt at about 7000°F. Most engineers agree that 6000°F is about the maximum gas temperature ultimately attainable in solid-fuel-element reactors after much research and development. The corresponding specific impulse would be about 1200 - 1500.

Rom then discusses the possible use of liquid-fuel-elements with hydrogen bubbling through, giving, if development proved possible, a specific impulse of 1500 - 1800. A further step is to consider a gaseous reactor with cooled walls, but this concept is still in the earliest exploratory phase.

The best appraisal of the present status of the development of nuclear rockets probably comes from the engineers and scientists of Project Rover. Durham gives a specific impulse of 800 stated as the early design objective and outlines the design considerations of a turbulent-flow solid-core heat-exchanger reactor. Bussard concluded that the specific impulse should be in the range 2000 to 5000 for hydrogen for a useful payload capacity on most missions of interest within the solar system, that the specific power output should be aimed for 0.5 to 1.5 megawatts per pound, which would require gaseous reactors at temperatures between 20,000° and 60,000°R.

There is a fairly universal feeling that nuclear rockets are a necessity for the more difficult missions in which substantial payloads are given very large velocity increments. As previously pointed out, the gain in specific impulse is in part offset by the greater weight of the nuclear rocket and this effect may be predominant if shielding is required.

According to Cotter the experiments now in progress represent a first but important step toward the development of a system, which will not at first be spectacularly better than chemical systems but which has great potentiality for development well beyond that possible for chemical systems.

Auxiliary Power

Nuclear energy is attractive as a source of energy for auxiliary power for use in satellites and space probes. The heat source may be a reactor or the energy of decay of radioisotopes may be used. In each case it is necessary to provide a conversion system to generate electrical energy from the heat energy, since most of the equipment in a space vehicle requires the energy in that form. The Atomic Energy Commission's Project SNAP is aimed at the development of systems for nuclear auxiliary power. NASA intends to support the development of energy-conversion devices and to co-sponsor the development of systems required in the space program.

Radioisotope sources are capable of supplying power over the range of 10 to a few hundred watts with presently available conversion devices at weights of 1.0 to 0.6 pounds per watt according to a survey by Robert C. Hamilton of the Jet Propulsion Laboratory published in the August 1959 issue of Astronautics. Devices dependent on radioisotope decay have a power output which decreases with time. The decay is at a slower rate for isotopes of long half-life. The power unit radiates, and the nature of the radiation from the specific isotope determines the amount of shielding and the precautions to be taken during launching. Only a few radioisotopes meet the requirements.

Thermoelectric converters of three types have been proposed for use with radioisotope sources. In the first, sometimes called the vacuum diode system, the heat energy is used to heat a hot plate which emits electrons to be collected on a cold plate, thus generating an electric current. The spacing must be very small in order to avoid limitations imposed by space charge. By the use of cesium vapor to form a conducting plasma the spacing may be increased to form what is often termed a plasma diode or plasma thermocouple. Finally a thermoelectric semiconductor may be used. Heat is transferred by conduction to the hot junction of a thermocouple.

In January 1959 the President described a demonstration unit, SNAP 3, developed under the sponsorship of the Atomic Energy Commission. Because it was readily available, polonium 210 was used as the source of heat, the hot junction of the thermocouple being heated to about 700°F. The cold junction temperature was about 180°F. The output was 3 1/2 watts of 0.1 volt and the weight was about 5 pounds.

All of these devices for direct conversion of thermal to electrical energy, although in their infancy, are also of interest for use with nuclear reactors as the heat source. Substantial increases in power density, operating temperature, and life are to be expected with further development.

For powers of 1 to 30 kilowatts, Hamilton suggests that reactors using turbo-alternators for conversion may be obtained at weights of 500 to 200 lbs. per kilowatt for unshielded and 1000 to 350 lbs. per kilowatt for shielded systems. Light weight and long life while unattended are the conflicting requirements for acceptable systems. Such systems require the rejection of heat by radiation from a large radiator, whose weight is a major factor in determining overall system weight. The radiator area and hence weight is affected by the choice of gas or metal vapor cycle.

Electric Propulsion

If a nuclear electric power system is required to meet the requirement of large amounts of auxiliary power, there are great advantages in using the same source for an electric propulsion system. Such systems using ion accelerators, plasma accelerators, arc jets, or one of the many other systems using charged particles or ions as working fluid generate only a small thrust but the propellant consumption is very low so that operation may be continued over a long period of time. Electric propulsion is well suited for propulsion in interplanetary space and for control of the orientation and orbit of earth satellites. Thus a nuclear electric turbo-alternator system may provide both propulsion and auxiliary power with resultant economy for some missions. Such a system must however function unattended for long periods, one or more years, and under conditions of zero gravity. As in all space equipment there is a large premium on light weight.

Special Research and Development Problems

The use of nuclear energy in space exploration requires an extensive supporting research and development effort on many special problems. For example, the greater weight of a nuclear rocket as compared with chemical rockets offsets to some extent the higher specific impulse, and efforts must be made to reduce the system weight. A key element is the reactor which must be as small as consistent with the required performance. Requirements for small size and high power lead to a high power density. High temperatures (4000°F and preferably higher) and the desire for light weight results in high thermal stresses in the reactor fuel elements. The high temperature leads to the need for excess reactivity. The change in phase of the hydrogen propellant, involving a density change by a factor of 20, affects the dynamics of the system. Finally there are problems of corrosion, erosion, fuel bleedout, power distribution. Some of these problems are discussed by Durham in the previously cited reference.

The problem of radiation damage in the nuclear rocket is unique by virtue of the high leakage fluxes and the wide temperature range that exists in the nuclear rocket. Payload, guidance, and control systems requiring transistorized circuits probably must be shielded. A really new area is the low temperature, high flux exposure of the liquid hydrogen pump and liquid hydrogen tank. Because of the total lack of information, NASA is negotiating a contract with the Marietta Division of Lockheed to conduct a research program on the effects of radiation on the mechanical properties of materials operating at cryogenic temperatures. It is anticipated that the radiation effects may be severe under these conditions because there is no annealing at these temperatures.

Reference has been made to the need for large radiators in nuclear turboelectric systems. This gives rise to the need for much research and development in previously unexplored areas. Thus if the working fluid is a vapor which condenses in the radiator, problems arise in the separation of liquid and vapor in a gravity-free field. The same problem is encountered in the venting of hydrogen in the propellant tanks when subject to radiant heating from the sun. In order to radiate heat, the surface of the radiator must have a high emissivity. The emissivity may change with time during exposure to the space environment. The usual high-emissivity coatings may be unsuitable in the space environment. Meteoroids may erode the surface, changing its emissivity, or, if large enough, may puncture the radiator to cause leaks.

Finally, the presence of radioisotopes and nuclear reactors in satellites and space probes necessitates the study of operational requirements for their safe use.

Conclusion

To return to the questions posed in the introduction, by way of summarizing:

(1) The potentialities of the use of nuclear energy in the exploration of space are very great indeed both for primary propulsive power and auxiliary power. In fact there are certain tasks involving large payloads accelerated to high velocities for deep space missions that can not be accomplished by any other practicable means.

(2) Nuclear energy will probably first find space application in auxiliary power systems within the next decade. These same systems will find use in electrical propulsion at a later time, perhaps also within the next decade. A practicable nuclear rocket will probably be demonstrated toward the end of this period, possibly as an upper stage of an interplanetary probe, the reactor being started after escape velocity has been reached.

(3) The great advance in nuclear technology required for space application is bound to bring benefits to all nuclear technology, especially when and if the reliability needed for distant space missions of long duration is realized in practice.